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Assessment of Coalescence Criteria for Steam Generator Tubes with Triple Axial Through-Wall Cracks

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Abstract

Recently, detection of diverse cracks has been increased world-widely in operating nuclear components such as reactor pressure vessels, SG(Steam Generator) and piping. Even though lots of efforts have been devoted to secure structural integrity of them, further researches are necessary especially for thin-walled SG tubes with multiple cracks. In this study, a preliminary assessment was conducted on dual axial through wall cracks(TWCs) in a representative SG tube and its validity was proven by comparing FE(Finite Element) analysis results with corresponding test data. Subsequently, by employing the assessment method, systematic FE analyses were carried out for triple axial TWCs in the same tube. Typical analysis conditions were selected on the basis of ASME B&PV code and main assessment was performed to examine whether the triple axial TWCs are behaved independently or merged. The details and key findings are fully discussed in this paper to decide the present criteria are appropriate or not, which can be used to develop further realistic coalescence diagrams of the multiple cracks.

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Keywords: Coalescnece pressure; Dual Axial Through-wall cracks; Finite Element Method; Plastic collapse pressure; Steam Generator Tube; Triple Axial Through-wall cracks

1. Introduction

A SG contains thousands of tubes with cover a major portion of reactor coolant pressure boundary. In view of its importance to sustain the integrity, SG tubes were plugged when a flaw exceeds 40% of wall thickness. However, the present criteria are too conservative for certain tube types, flaw configurations and locations [1]. Even though

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lots of efforts have been dedicated to develop alternative plugging criteria, further researches are required for multiple axial TWCs in SG tubes.

In the previous studies [1-5], assessment methods and parametric FE analysis were examined by comparing FE analyses results and corresponding test data for dual axial TWCs in a SG tube. Subsequently, in this study, the proven methods are expanded and applied for the triple axial TWCs in the same tube. These results can be used to evaluate whether the triple cracks behave independently or merge into realistic coalescence conditions.

2. Assessment Criteria, Methods and Their Validation

2.1. Coalescence criteria

Figure 1 depicts the tubes containing three types of dual-axial TWCs. The crack length is 2*c,* axial distances between two cracks are denoted by *d* and radial distances are denoted by *h*. Specially, non-aligned cracks were classified as type A(*d*>0), B(*d*=0) and C(*d*<0) according to axial distance [1-5].

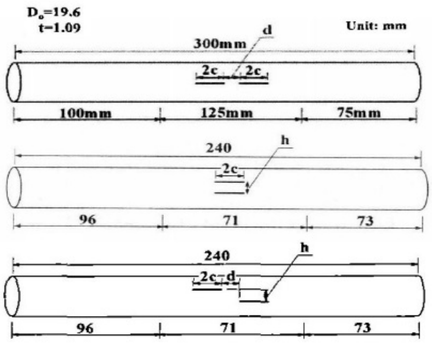

Fig. 1. Schematic illustration of tube containing dual axial TWCs [3-5].

The coalescence criteria were decided by comparing failure pressures of dual crack with those of ESC(Equivalent Single Crack). The ESC was described in The ASME (American Society of Mechanical Engineers) code and calculated by using Eq. (1) [6].

$$2c_{esc} = 2c_1 + 2c_2 + d \tag{1}$$

The failure pressure of ESC can be calculated by Eq. (2) for tubes with a single TWC [7].

$$P_{cr} = \frac{\sigma_f t}{M_T R} \tag{2}$$

$$M_T = 0.614 + 0.481\lambda + 0.386\exp\left(-1.25\lambda\right), \text{ for } \quad 5 \le R/t \le 50 \tag{3}$$

$$\lambda = \left[12\left(1-\nu^2\right)\right]^{0.25}\left(\frac{c}{\sqrt{Rt}}\right) \tag{4}$$

where, σ_f is the flow stress, t is the wall thickness, R is the mean radius of SG tubes, M_T is the bulging factor calculated by Eq. (3), λ is the shell parameter calculated by Eq. (4), ν is the Poisson's ratio and c is the half length of the crack.

2.2. Assessment methods

In the previous studies, optimum failure prediction models like PZC-II, PZC-IV and COD were proposed for each crack type. The main features of these models are briefly described as follows [1-4].

(1) Plastic Zone Contact model II(PZC-II): It is assumed that coalescence could be occurred when plastic zones developed from the crack-tip come into contact. This model is based on the contour plot of the von Mises stress which equals to the tensile strength.
(2) Plastic Zone Contact model IV(PZC-IV): It is assumed that coalescence could be occurred when the remaining ligament between cracks is fully yielded. This model is based on the contour plot of the von Mises stress, which equals to the tensile strength.
(3) Crack Open Displacement(COD) model: It is assumed that the plastic collapse of tubes could be occurred when the COD at each of two parallel cracks is equal to the COD of single crack at the failure load.

2.3. Application to dual cracks

Among the three failure prediction models described in section 2.2, PZC-IV model was selected as an optimum model for dual collinear axial TWCs and COD model was recommended for dual parallel axial TWCs and type B and C of dual non-aligned TWCs. Meanwhile, PZC-II model was selected as optimum one for type A of dual non-aligned axial TWCs.

2.4. Results and discussion

Figure 2(a) and 2(b) show the preliminary analysis results of coalescence and/or failure pressures of collinear and parallel cracks compared with previous experiment ones. The analysis results were comparable to previous results well. In 4mm of ligament length, an analysis result was greater than the corresponding experiment one however the difference was 8%. So, it seems applicable to triple cracks.

Figure 2(c) shows the preliminary analysis results of coalescence and/or failure pressures of non-aligned axial cracks compared with the corresponding experiment ones for type A, B and C. Similar tendencies were obtained with those of the preceding data.

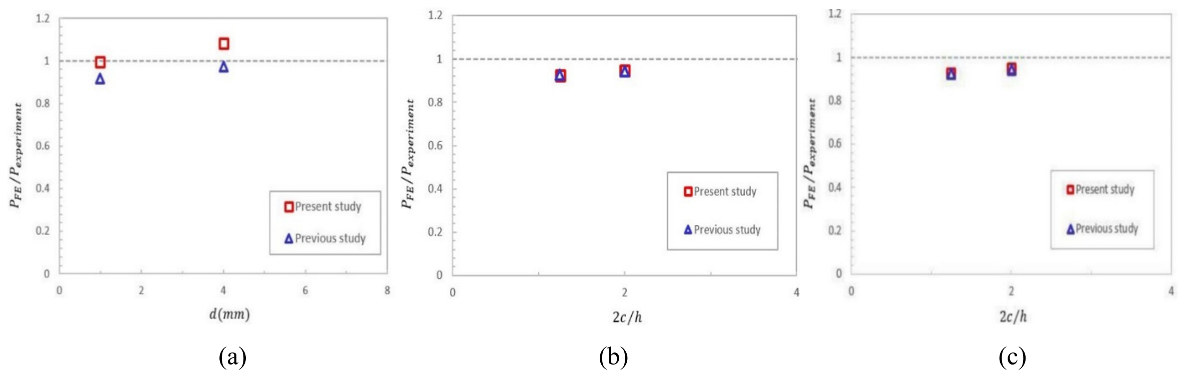

Fig. 2. (a) Result of dual collinear axial TWCs; (b) Result of dual parallel axial TWCs; (c) Result of dual non-aligned axial TWCs.

3. Assessment of Triple Cracks

3.1. Analysis conditions

Figure 3 shows the schematics of triple axial TWCs described in ASME code. Based on this reference, analysis cases were determined for collinear, parallel and non-aligned axial TWCs. The mechanical properties of alloy 600 and analysis cases used in this study were summarized in Table 1 and Table 2, respectively.

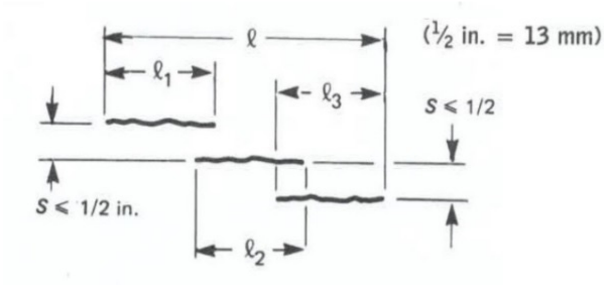

Fig. 3. Schematics of triple axial TWCs according to ASME code [6].

Table 1 Mechanical properties of alloy 600 [1].

Yield strength	Tensile strength	Young's modulus	Elongation	Poisson's ratio
σ_y (MPa)	σ_u (MPa)	E (GPa)	(%)	ν
285	674	214	40	0.3

Table 2. Analysis cases.

Collinear axial TWCs		Parallel axial TWCs		Non-aligned axial TWCs								
				Type A			Type B			Type C		
$2c$ (mm) $l_1=l_2=l_3$	d (mm)	$2c$ (mm) $l_1=l_2=l_3$	h (mm)	$2c$ (mm) $l_1=l_2=l_3$	d (mm)	h (mm)	$2c$ (mm) $l_1=l_2=l_3$	d (mm)	h (mm)	$2c$ (mm) $l_1=l_2=l_3$	d (mm)	h (mm)
	1		2			2			2			2
	2		4	5	2	4	5	0	4	5	-2.5	4
5	4	5	8			8			8			8
	5		-	-	-	-	-	-	-	-	-	-
	7		-	-	-	-	-	-	-	-	-	-

3.2. FE models and analyses

Figure 4 show typical 3D FE models of the triple collinear, parallel and non-aligned axial TWCs. These were developed by taking into account for symmetric conditions as one half respectively. Relative data such as number of elements, nodes and element types were summarized in Table 3. In order to incorporate material property as isotropic elasto-plastic behavior that obeys J2 flow theory, true stress-strain data of alloy 600 were used [3]. Also, RIKS and NLGEOM options provided by ABAQUS were used for FE analyses [3,8].

As described in section 2.3, the triple collinear cracks were evaluated by PZC-IV model. The parallel, type B and C of non-aligned cracks were evaluated by COD model and type A of non-aligned cracks was evaluated by PZC-II model.

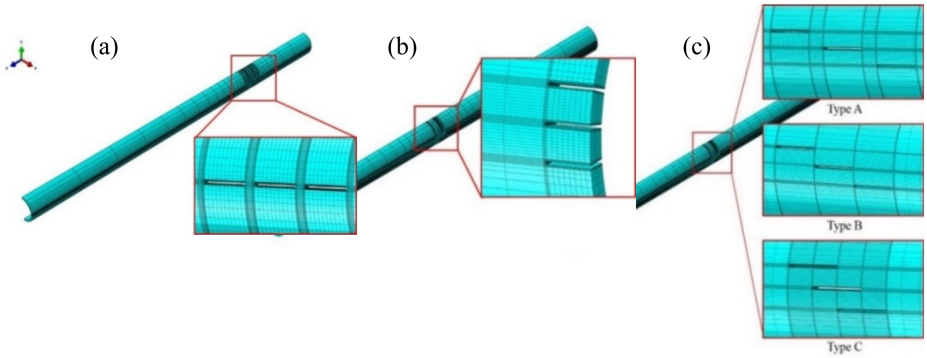

Fig. 4. (a) Triple collinear axial TWCs; (b) Triple parallel axial TWCs; (c) Triple non-aligned axial TWCs of Representative FE models.

Table 3. Relative data of FE models.

Category	Collinear	Parallel	Non-aligned		
	(2*c*=5mm, *d*=1mm)	(2*c*=5mm, *h*=2mm)	Type A (2*c*=5mm, *d*=2mm, *h*=2mm)	Type B (2*c*=5mm, *d*=0mm, *h*=2mm)	Type C (2*c*=5mm, *d*=-2.5mm, *h*=2mm)
Element types	C3D20R	C3D20R	C3D20R	C3D20R	C3D20R
Number of element	13,460	3,736	16,992	12,744	20,280
Number of node	76,220	21,753	95,782	72,146	114,730

3.3. Results and discussion

Figure 5 shows analysis results for collinear cracks, in which coalescence and/or failure pressures of the dual and triple cracks were compared with plastic collapse pressures of the ESC. The coalescence pressure means the pressure when dual or triple cracks merge into a single crack. On the other hand, the plastic collapse pressure means the pressure when a single crack causes overall structural instability. In general, the coalescence pressures were decreased as an increase of crack numbers and an decrease of ligament distance. Therefore, the coalescence and/or failure pressures of the triple cracks were lower than those of dual cracks.

Meanwhile, in previous studies, the interaction effect between two adjacent identical cracks disappeared when the ligament length exceeded 4 mm and the two identical cracks behaved like independent single cracks [1]. However, since the resulting pressures of triple cracks were lower than those of dual cracks, it is anticipated that they behave like independent single cracks even though the crack distances larger than 4 mm.

Also, by comparing with the plastic collapse pressures of the ESC, as an increase of distance between cracks, the resulting pressures were decreased. Because ESC is sum of three crack lengths and crack distances so, the crack size was increased with an increase of crack distances. Therefore, it seems that the criteria presented in ASME code is conservative.

Figure 6 shows analysis results for parallel cracks, in which failure pressures of the dual and triple cracks were compared with plastic collapse pressures of the ESC. Since the equivalent single crack lengths were equal to individual cracks, it was determined that identical cracks behaved like independent single crack in cases of parallel cracks. Also, interaction effect not occurred when the ligaments are smaller than those of the ESC and dual cracks.

In cases of dual cracks, the interaction effect occurred when the crack distance was larger than 4 mm. On the other hand, in cases of triple cracks, the interaction effect occurred when the crack distance was smaller than 2mm. It can be understand that the failure pressures were decreased as an increase of crack numbers.

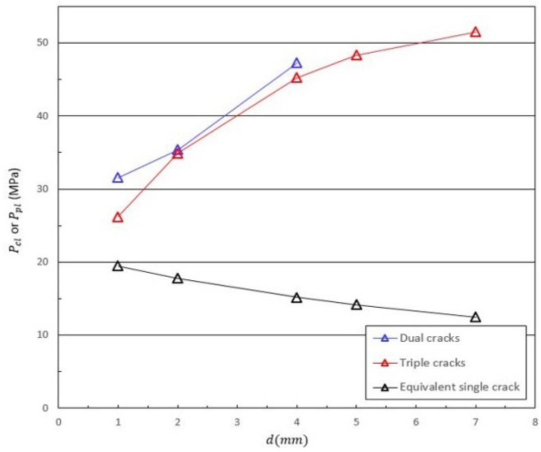

Fig. 5. Comparison of analysis results for collinear cracks.

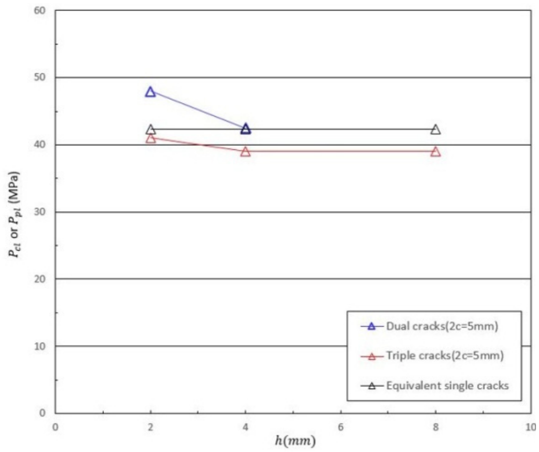

Fig. 6. Comparison of analysis results for parallel cracks.

Figure 7 shows analysis results for non-aligned cracks, in which coalescence and/or failure pressures of the dual and triple cracks were compared with plastic collapse pressures of the ESC. Similar to the previous studies, overall coalescence or plastic collapse pressures were decreased as an increase of crack numbers.

In cases of type A, overall behavior were similar to results of the collinear axial TWCs so, the resulting pressures were decreased as an decreasing crack distance and an increase of crack numbers.

In cases of type B, the resulting pressures were also decreased as the increase of crack numbers. In addition, it was observed that the criteria of interaction effect in accordance with radial distance were changed. Particularly, the interaction effect occurred to be coalesced well if the crack distance was less than 6mm.

In cases of type C, the resulting pressures were also decreased like other cases. Because the crack distance was closer, coalescence pressures were smaller than those of type B and the criteria of interaction effect were also changed.

Meanwhile, overall tendencies of coalescence pressures were different with those of parallel cracks though the interaction effect occurred. Particularly, it was observed that there was radial distance effect as well as axial distance effect. Moreover, with regard to the coalescence pressures of ESCs defined in ASME code were similar with collinear axial cracks. As the increase of the distance between cracks, plastic collapses were decreased so that the plastic collapse pressures seemed more conservative than the actual behavior.

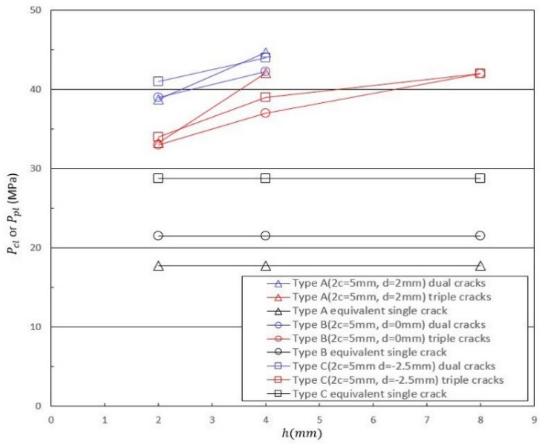

Fig. 7. Comparison of analysis results for non-aligned cracks.

4. Conclusions

In this study, the coalescence and/or failure pressures of SG tube with triple axial TWCs were evaluated through systematic FE analyses. It is anticipated that these results can be used to develop further realistic coalescence diagrams for the triple cracks, from which the following conclusions were made.

(1) In cases of collinear cracks, coalescence pressures were decreased as an increase the number of cracks and each of cracks behaved like independently when crack distances were larger than 4 mm.
(2) In cases of parallel cracks, it is expected that individual crack behavior occurred less than 2 mm and coalescence was occurred by interaction effect well in greater than 2 mm.
(3) In cases of non-aligned cracks, they were similar with collinear axial cracks overall. And it showed some different tendencies with parallel cracks. Because there was not only radial distance effect also axial distance effect.

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